

# **Investigation of Ship Flight Deck Motion Limits for Safe Embarked Helicopter Operation**

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## **ABSTRACT**

The limitations of conventional displacement measures for quantifying the severity of flight deck motions as they affect helicopter securing requirements are illuminated. Alternative improved measures based on equivalent acceleration parameters are introduced and discussed. The paper then differentiates between passive and active securing principles as they are usually applied and demonstrates with study results that passive securing is advantageous for securing intermediate and heavy helicopters.

## **INTRODUCTION**

Navies around the globe recognise the importance of operating helicopters from frigate-sized ships. Anti-submarine warfare and search and rescue capabilities are substantially improved by the presence of helicopters onboard. To realise such improved capabilities, the helicopter operation must be possible in high sea conditions in which flight deck motions become extremely severe. The limits for embarked aircraft operations, which depend on the aircraft securing method, historically have been specified in terms of sea state (essentially a probabilistic description of the amplitude and frequency distribution of waves in a seaway) and angular displacements of the ship (typically roll and pitch angles). Similarly, acceptable landing windows during quiescent periods have been defined by limits on ship angular displacements. For example, operating limits currently may be stated as, "...limited to sea state 5 with landings occurring when the ship roll is less than 8 degrees and ship pitch is less than 3 degrees."

The shortcomings of this approach for defining operating limits quickly become apparent. First, the severity of aircraft loading, and the magnitude of securing requirements, are not directly related to displacements but rather acceleration at the flight deck. Second, landing conditions and securing

requirements at the flight deck are influenced by numerous factors, such as ship hull design; flight deck location; ship operating conditions including heading, speed, and loading; and embarked aircraft dynamic characteristics. Suitable parameters for identifying the true severity of conditions at the flight deck clearly need to include the effect of all these factors. However, flight deck motion limits should also be established independent of specific combinations of these factors. It is therefore desirable to establish flight deck operating limits that are physically measurable in service for a particular aircraft and its method for on-deck securing.

Recognising the limitations of conventionally established operating limits, Indal Technologies Inc. (ITI), a developer of marine aircraft handling systems, has developed the concept of equivalent acceleration. The concept combines factors affecting flight deck conditions into meaningful parameters. Analysis has shown that the concept is very effective for establishing securing system design requirements and consequently also for defining the deck motion limits for safe helicopter operations.

A further parameter called the T-Factor has recently been developed to extend the concept of equivalent acceleration to include the effect of the rotor loads which are functions of the ship's angular motion.

This paper will discuss the merits of the equivalent acceleration and T-Factor parameters and their use in defining the on-deck helicopter operating limits. Furthermore, the effects of various securing methods on those limits will be explained and demonstrated.

Time histories of the forces and relative displacements that result from the dynamic interface between the helicopter and ship are developed using ITI's proprietary *Dynaface*<sup>®</sup> dynamic interface simulation software [1,2]. The simulation and associated analysis methodology has evolved over the past decade and is used extensively by ITI and others under licence from ITI for the analysis of the

dynamic interface problem. Comparison with other simulation results, analytical solutions, rig suspension test results, and both land-based and sea trial experimental results have validated the simulation. The time histories generated by *Dynaface*<sup>®</sup> are then analysed to extract appropriate interface parameters

## FLIGHT DECK MOTION ANALYSIS

Flight deck motion analysis is aimed at characterising the motions and environmental conditions at the flight deck in typical and severe operating conditions. The current preferred approach is to evaluate ship motions for extended time periods using either linear or nonlinear ship motion simulation methodologies and then investigate the ship motion time histories to identify potentially severe conditions to use as input for performing subsequent aircraft response simulation. The motivation for this stems from the relatively high speed at which linear ship motions can be evaluated compared with the slower speed of detailed aircraft response analysis. To reduce the amount of computer simulation that must be performed to conduct a complete analysis, it is essential to quantify the severity of the motion in a way that guides the selection of the critical simulation cases. One approach is to scan the ship motion time histories for the maximum motion component amplitudes and to plot these as a function of heading and speed. The upper part of Figure 1 shows a polar plot of the worst case roll amplitudes corresponding to sea state 6 conditions for a typical 4200 ton frigate (where 0° corresponds to head seas).

Ship motions are usually evaluated at the ship origin which is typically the intersection of a vertical line through the centre of mass of the ship and the undisturbed free sea surface. As mentioned previously, while ship displacements may provide an indication of the severity of the ship motion, it is the total linear acceleration at the flight deck that directly affects helicopter securing.

### Equivalent Acceleration

The concept of equivalent acceleration, in its simplified planar form, is illustrated schematically in Figure 2. The total acceleration at the flight deck is comprised of the linear acceleration resulting from ship kinematics and from the instantaneous component of the acceleration due to gravity. Equivalent acceleration effectively combines the effects of both the deck inertial acceleration and angular displacement of the ship as it affects the aircraft/ship dynamic interface. For analysis, it is more appropriate to resolve the total acceleration into

components parallel and perpendicular to the plane of the deck. The components are referred to as the horizontal equivalent acceleration and the vertical equivalent acceleration respectively. Increased horizontal equivalent acceleration indicates increased lateral loading on the aircraft in the plane of the deck. Reduced vertical equivalent acceleration indicates reduced contact force between the aircraft and the deck, and correspondingly reduced potential for developing frictional force to oppose aircraft sliding. Consequently, the ratio of horizontal equivalent acceleration to vertical equivalent acceleration generally quantifies the tendency of a conventional unsecured aircraft to slide as the result of ship motion.

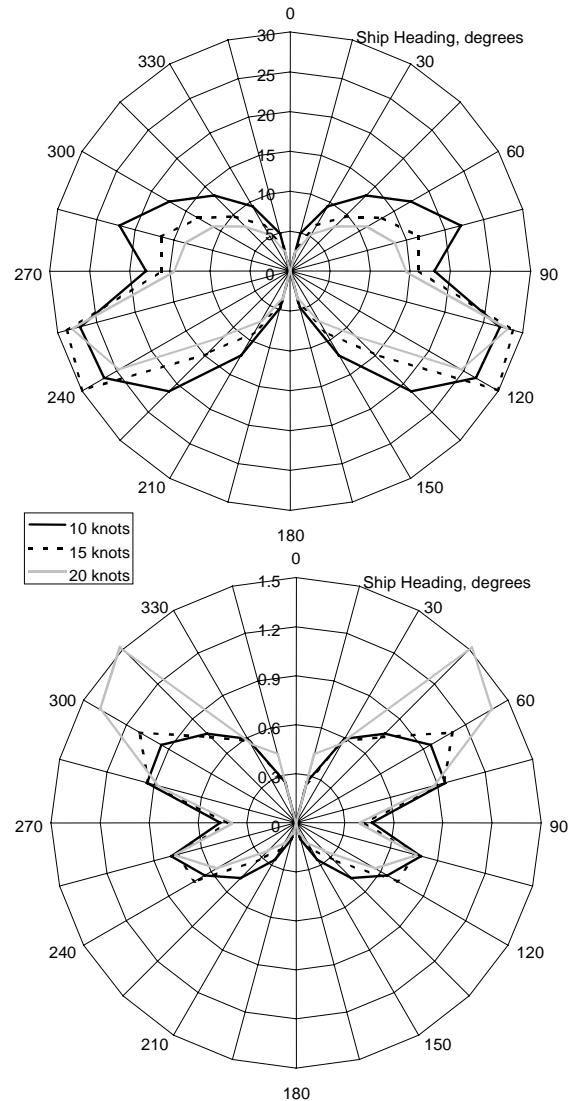


Figure 1: Typical frigate peak roll angle in degrees (upper) and peak equivalent acceleration ratio (lower) for operation in severe sea conditions as a function of ship heading and ship speed.

Consider the two peak motion parameters for a typical frigate operating in severe sea conditions presented in Figure 1. The upper plot of roll angle suggests that the most severe conditions occur at headings of  $\pm 120$  degrees. The lower plot presents the peak equivalent acceleration ratio. The peak occurs at headings of  $\pm 45$  degrees. Clearly, in this example, erroneous conclusions about the severity of ship motion at headings of  $\pm 120$  degrees would be drawn based on the traditional roll measure of flight deck motion while the real severe conditions occur at headings of  $\pm 45$  degrees.

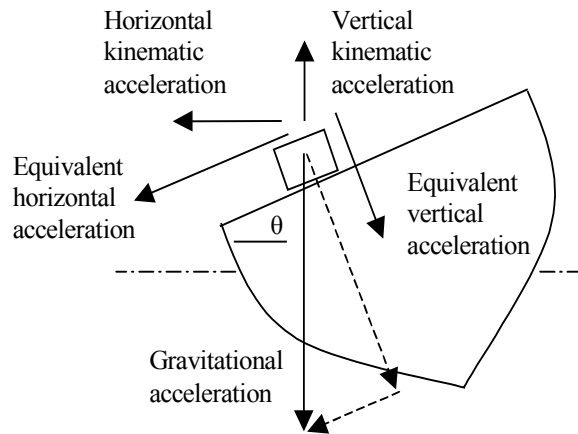


Figure 2: Schematic planar representation of the concept of equivalent acceleration

### T-Factor

In the previous section, the forces due to the wind over the flight deck were not included in the definition of equivalent acceleration. Although the fuselage drag forces are relatively small when compared with the gravitational forces, the main rotor induced forces are significant and must not be ignored in calculating the helicopter securing requirements. For the case of a helicopter after landing, ITI's studies, including wind tunnel testing, have proven that the rotor thrust generated by the wind over the deck may exceed 25% of the helicopter weight. The thrust generated by a turning rotor, while the helicopter is on deck with the rotor set at its minimum collective, depends on the rotor disc angle relative to the wind. This angle is function of the ship roll and pitch motion. To include the effect of the rotor thrust, the ratio of the rotor thrust to the helicopter weight is calculated for each ship heading and speed assuming a 30 knot beam wind. The thrust ratio is then added to the vertical equivalent acceleration before calculating the ratio between the

lateral and vertical components of the accelerations. The new ratio characterises the Tendency of an Aircraft on Deck (with the Rotor On) to Slide and may be called the T-Factor:

$$\text{T-Factor} = |\text{lateral equiv. acceleration} / (\text{vertical equiv. acceleration} - \text{thrust ratio})|$$

where the thrust ratio is given by  $0.25 * |\text{Roll}| / 20$  up to a maximum of 0.25G with the accelerations in Gs and the roll angle in degrees. This expression reflects linear variation of induced rotor thrust with rotor angle of attack (approximately equal to the roll angle) up to a maximum 0.25G at 20 degrees.

The equivalent acceleration based parameters often indicate severe securing conditions for ship operating conditions that are not indicated by conventional displacement measures. By including the effect of wind, the T-Factor can provide an effective means for defining the worst case conditions for subsequent use in simulation. The T-Factor can also be used as a comparative parameter for evaluating the expected relative securing requirements for various helicopters.

The effectiveness of the T-Factor for identifying severe aircraft securing conditions is demonstrated in Figure 3. The plot shows the variation with time of the radial and vertical components of the securing force for a typical ITI ASIST system (see Figure 8) securing an intermediate-sized helicopter in severe sea conditions. The frigate motion corresponding to this plot was simulated using *SMP* [3] and *ShipSim* [4]. Figure 3 also shows the variation of the T-Factor with time. While the simulation duration was 30000 seconds, only the 200-second segment containing the maximum securing forces is shown. The arrows on the plot indicate the peak values of the radial securing force, vertical securing force, and T-Factor. It is evident that the T-Factor successfully identified the ship motion corresponding to the most demanding securing requirements. The aircraft response simulations are typically run for 30 seconds surrounding potentially severe ship motion parameters (such as the T-Factor) so that any time lags between peak ship motion events and peak securing forces are captured. Further, it is important to simulate the transient behaviour surrounding peak events to understand how the system reacts rather than merely identifying instantaneous peak values. The equivalent accelerations and T-Factor are effective in selecting the potentially severe conditions.

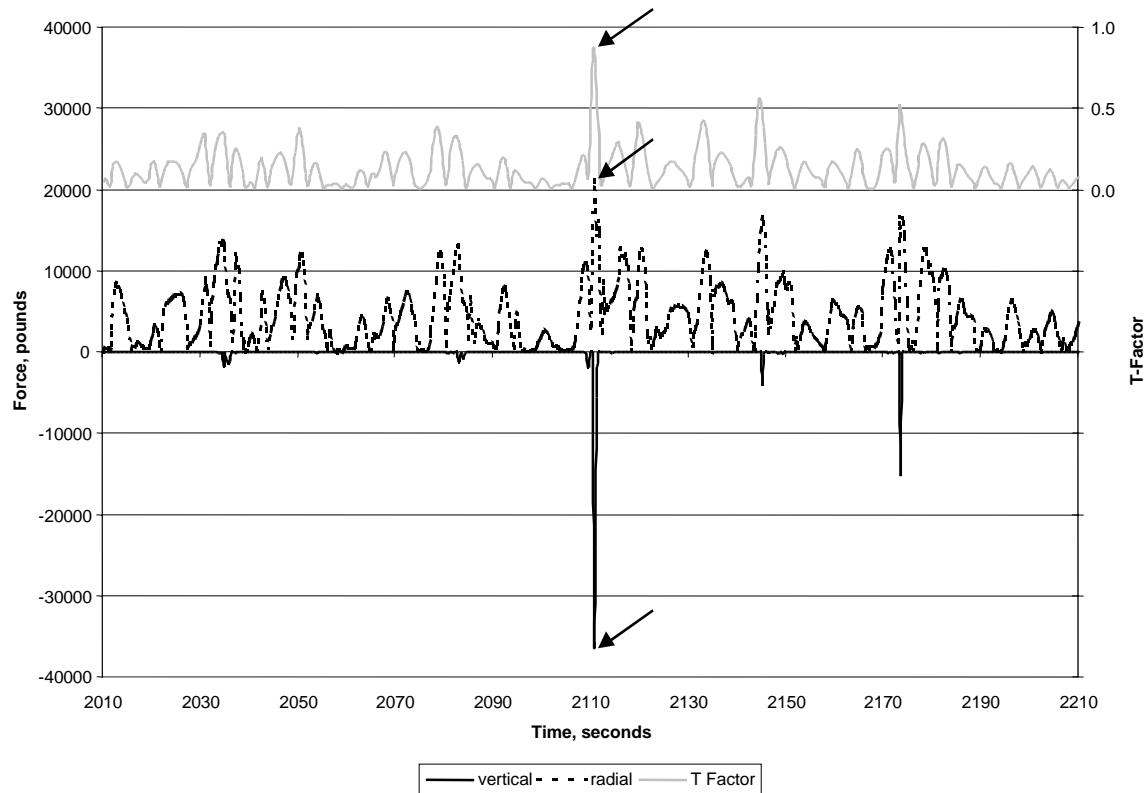


Figure 3: Variation of radial and vertical securing forces and T-Factor with time.

Equivalent acceleration based parameters provide an effective means for quantifying tendency. However, the actual aircraft behaviour and corresponding interface parameters can only be evaluated from simulation of the aircraft response due to the strong nonlinearity of the aircraft/ship system.

### AIRCRAFT RESPONSE ANALYSIS

Typical on-deck securing situations are illustrated in Figure 4, both pictorially and schematically for similar though slightly different securing conditions. The objectives of on-deck dynamic interface simulation are to mathematically represent the in-service aircraft and ship system with sufficient fidelity to gain insight into the dynamic interface behaviour yet maximise simulation speed such that very large numbers of simulation cases can readily be investigated during a single study.

*Dynaface*<sup>®</sup> consists of a special-purpose 15-degree-of-freedom mathematical model of the aircraft/ship system. While the simulation is special purpose to promote solution efficiency, it includes sufficient generality such that a large variety of aircraft and virtually all ships can readily be modelled. The simulation currently contains prismatic oleo and

leading/trailing arm suspension models having up to two wheels each that can be attached to the fuselage in either nose wheel or tail wheel configurations, up to two main rotors, and a large variety of possible securing devices. The model includes detailed representations of the oleo stiffness, damping, and friction characteristics; induced rotor forces; and a detailed nonlinear tire model that supports complex tire behaviour including lift-off and touch-down, rolling due to suspension travel, brake slippage, and sliding.

Computationally, speed is maximised by removing physically impossible discontinuities from model characteristics, carefully controlling coupling between model degrees of freedom, and carefully matching the numerical integration with the equation structure. These considerations have led to a simulation that meets the objectives of accuracy and speed. The aircraft and ship configurations, environmental conditions, and simulation control parameters are specified in a set of input files. The simulation uses this information to describe the physical system. It then generates the time-varying prescribed ship motion and propagates a time-domain solution by numerically integrating the governing equations of motion for the system. An exhaustive

set of optional results; including aircraft relative angular displacements, securing forces, landing gear reaction forces, suspension forces, tire deflections, induced aerodynamic forces, and animation data; are saved in a selected subset of 18 available output files. Simulation results are post-processed by a suite of utility programs or animated using either two- or three-dimensional animation software tools.

While the forces acting on the helicopter are a function of the helicopter characteristics and the deck conditions, the securing forces are largely affected by the method of the securing as discussed in the following section. Model complexity arises from the nonlinearity and range of behaviours associated with the various force-producing elements in the model.

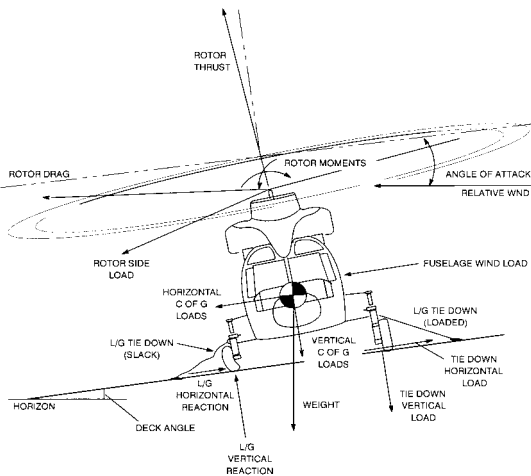


Figure 4: Identification of forces acting on a secured aircraft

### SECURING REQUIREMENTS

The performance of a helicopter securing system must account for the dynamic interface conditions between the helicopter and the ship to meet the fundamental requirement for securing. Since

helicopter securing reflects safety aspects regarding personnel during on-deck helicopter operations, a quantitative definition of helicopter securing was developed as follow:

For a helicopter to be considered 'secure', two criteria must be satisfied:

- Excessive motion must be prevented; and
- tire sliding must not occur.

The motion limits beyond which motion is considered excessive are the maximum relative angular motions that can occur corresponding to one oleo being fully extended with the other two being fully compressed. Tire sliding involves a permanent shift of one or more tire/deck contact points.

While it is widely known that a variety of conditions affect the securing requirements for a helicopter on a frigate-sized ship such as the one illustrated in Figure 5, the effects of ship design have been discussed extensively in Reference [5], and the effect of sea conditions and ship operating conditions have been addressed to some extent in Reference [6]. Consequently, this paper focuses on the effect of the method of securing on the securing requirements and explores the differences between two principles for securing embarked aircraft upon landing. The interface parameters of a secured helicopter (landing gear reactions, helicopter movements relative to the deck, and securing loads) vary considerably depending on the underlying principle upon which the securing system is based.



Figure 5: Typical frigate moving through waves

All securing systems can be classified in one of two categories – passive and active, as described below. The two securing principles are illustrated schematically in Figure 6.

a) Passive securing systems are those in which one or more structural members fitted to the helicopter and fixed to the ship react the helicopter loads, restraining

the helicopter from excessive movement and transferring the loads into the ship's structure. Securing is limited only by the strength of the securing member(s) and the supporting structure.

b) Active securing systems are those in which a mechanical/hydraulic device, fitted to the helicopter and attached to the ship, continuously applies a constant force in an effort to create sufficient friction to prevent tire sliding. Securing is limited by the magnitude of the force, the extension of the securing element(s) under load, the landing gear capacity, the tire deflection limits, and the deck coefficient of friction.

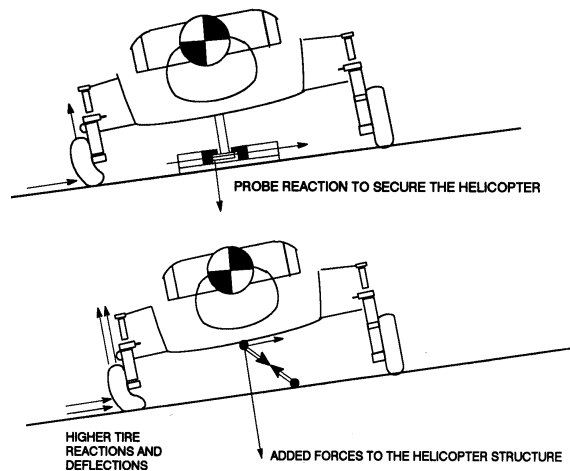


Figure 6: Schematic representation of passive (upper) and active (lower) securing principles

The selection of securing principle not only affects securing loads, as indicated above, but also directly influences how the second part of the securing definition is satisfied. Consider the schematic illustrations in Figure 7. The left sketch corresponds to an aircraft secured by a single point passive system such as an ITI probe system as pictured in Figure 8. The right sketch corresponds to a single point constant tension link system. In the case of the passive system (left sketch), the probe, which is generally mounted in the aircraft close to the centre of mass, forms a fixed point of rotation between the helicopter and ship. Consequently, the only mode by which tire sliding can occur is aircraft yaw about the fixed point of rotation. For this to occur, all tires must become saturated such that they cannot generate sufficient friction to produce the frictional moment about the fixed point of rotation required to resist aircraft relative yawing. In the case of a single constant tension link (right figure), the securing system essentially acts as a constant-tension spring between a point generally close to the centre of rotation of the helicopter and the ship. As this system

does not form a fixed point of rotation, two instability modes are possible that can result in tire sliding and correspondingly failure to satisfy the securing definition. The first instability mode is pure translation of the aircraft; the second is pure rotation (in yaw) of the aircraft. Dynamic analysis studies consistently show that sliding manifests itself as a combination of the two modes such that the aircraft yaws about an instant centre of rotation. This is the situation illustrated in Figure 7 where rotation occurs about the main gear located in the lower left of the sketch (the same rationale applies to both nose and tail gear aircraft). The result is that loss of securing can occur when only two landing gear (rather than three in the case of a single passive probe system) reach their frictional saturation limit.

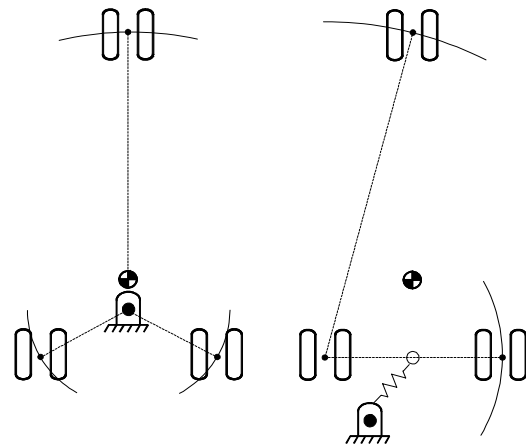


Figure 7: Schematic representation of fixed point of rotation created by a single point passive securing system (left) and the usual instability mode associated with single point constant-tension securing systems where yaw tends to occur about an instant centre of rotation located at a main landing gear (right)



Figure 8: ITI's passive ASIST securing system securing an intermediate-sized helicopter

A dynamic interface analysis study was conducted using a heavy helicopter secured to a typical frigate in upper sea state 6 conditions (characterised by 6.0-metre significant wave height and an apparent wind speed of 35 knots from the beam). The securing

definition (described earlier) was applied in post-processing the results and the resulting operational envelopes are presented in Figure 9. Shaded areas indicate ship headings where the securing definition is *not* satisfied. The results indicate that for the helicopter/ship combination considered, the heavy aircraft fitted with the probe system can be considered secure for all combinations of ship heading and ship speed in sea states 5 and 6. The operational envelope for the constant tension link secured aircraft is limited to ship headings from  $0^\circ$  to  $\pm 37.5^\circ$  and from  $\pm 112.5^\circ$  to  $180^\circ$  in sea state 5 and from  $0^\circ$  to  $\pm 22^\circ$  and from  $\pm 112.5^\circ$  to  $180^\circ$  in sea state 6. As all other parameters remained constant, this difference can only be attributed to the securing principle. The envelopes are a function of the system simulated, however the tendencies are generally applicable.

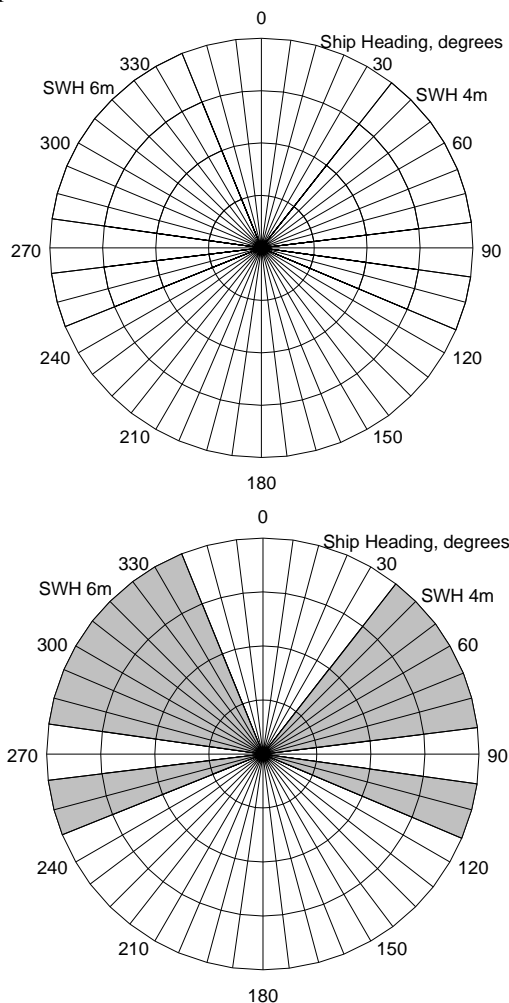


Figure 9: Ship headings where a heavy aircraft does not satisfy the securing definition for a passive probe system (upper) and a constant tension link (lower) in seas characterised by both 4 and 6 metre significant wave heights (SWH)

## DISCUSSION AND CONCLUSION

ITI is continually applying proven expertise in the field of aircraft/ship dynamic interface analysis to further explore factors affecting aircraft securing requirements. The objectives are to maximise availability of aircraft for takeoff and landing to the full operating envelopes of the helicopter and ship, ensure the safety of personnel and equipment; provide continuous indication of the severity of flight deck conditions; and promote consistency in how securing equipment design limits are established.

This paper has briefly addressed the limitations of conventional measures of flight deck motion and demonstrated that concepts and measures related to equivalent acceleration offer a truer quantification of the severity of flight deck securing conditions for the safety of embarked operations involving helicopters. The main factors affecting helicopter embarked securing requirements were discussed. However, the primary focus of the second portion of the paper was to illuminate fundamental differences between two alternative securing principles and the implications for the safety of embarked operations involving intermediate and heavy helicopters. Study results indicate that constant tension active systems are unable to secure intermediate and large helicopters without using excessively high tensions that potentially exceed those acceptable for landing gear design limits. The results also indicate that passive devices provide securing of intermediate and heavy helicopters over a wider range of the ship operating envelope.

## REFERENCES

- [1] Langlois, R. G. and Tadros A. R., 'User's Manual for the Aircraft/Ship Dynamic Interface Simulation Program', ITI Report 99-419, Indal Technologies Inc., Mississauga, Ontario, Canada, February 1999.
- [2] Langlois, R. G. and Tadros A. R., 'Modelling the Aircraft/Ship Dynamic Interface', Presented at the 16<sup>th</sup> Canadian Congress of Applied Mechanics, Québec City, Québec, Canada, June 01 – 05, 1997.
- [3] Meyers, W. G., Applebee, T. R. and Baitis, A. E. 'User's Manual for the Standard Ship Motion Program', SMP. David W. Taylor Naval Ship Research and Development Centre, Bethesda, Maryland, USA, September 1981. Report No. DTNSRDC/SPD-0936-01.

- [4] Vernooy, L. and Langlois, R. G., 'User's Guide for the *ShipSim* 4.2 Ship Motion Simulation Program', Indal Technologies Inc., Mississauga, Ontario, Canada, August 1999.
- [5] Tadros, A. R., Sopher, G., and Langlois, R.G., 'A New Approach for Passive Securing at Landing and Powered Handling of Helicopters Onboard Small Ships', WARSHIP '98 International Symposium on Surface Warships: The Next Generation, London, June 1998.
- [6] Langlois, R., Moquin, D., and Rocconella, B. 'Consideration of the Effect of Securing and Traversing Loads on the Fatigue Life of the Kaman Seasprite RAST/ASIST PROBE Installation', Presented at the American Helicopter Society 55<sup>th</sup> Annual Forum, Montreal, Québec, Canada, May 25 – 27, 1999.



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